NANOMETAL-INTERCONNECTED CARBON CONDUCTORS (NICCs) FOR ADVANCED ELECTRIC MACHINES

DE-EE0007863

Rochester Institute of Technology, US Naval Research Labs, Nanocomp Technologies, MN Wire and Cable

April 1, 2017 – March 31, 2020

Dr. Brian J. Landi, Rochester Institute of Technology (PI)
Dr. Cory D. Cress, U.S. Naval Research Laboratory (Co-PI)

U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
June 11-12, 2019

Overview

Timeline

- RIT Award Issued April 2017
- NCTI Subcontract July 2017
- NRL directly funded by DOE
- Project Complete March 2020
- Project ~70% Complete

RIT

Landi Research Group

Barriers

- Research needed to overcome CNT transport in bulk conductors by nanoscale alignment, chemical doping, and selective metallic interconnection; which achieves superior electrical performance over metals in a 28 AWG wire for electric machine applications.

Project Budget and Costs

Budget	DOE Share	Cost Share	Total	Cost Share %
Overall Budget	$1,000,000	$163,130	$1,163,130	13.9%
Approved Budget (BP-1&2)	$666,680	$107,316	$773,996	13.9%
Costs as of 3/31/19	$647,209	$129,111	$776,321	13.9%

Partners

- U.S. Naval Research Laboratory (NRL): Dr. Cory Cress – CNT modification and evaluation

U.S. NAVAL RESEARCH LABORATORY

- Nanocomp Technologies Incorporated (NCTI): Mr. Eitan Zeira, Dr. Mark Schauer – Scalability and wire production

nanocomp TECHNOLOGIES, INC. A Huntsman Company

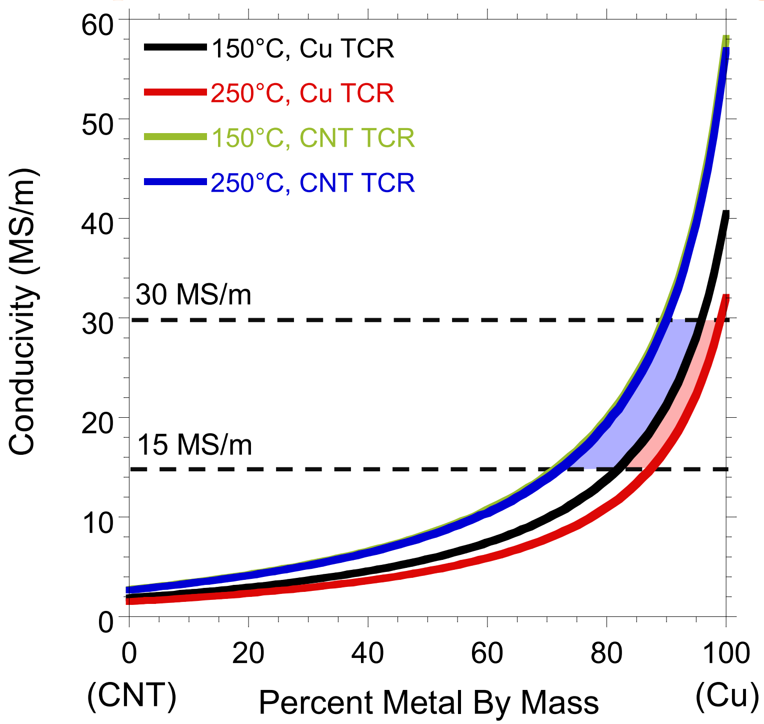
- Minnesota Wire (MW): Mr. Tom Kukowski – Scalability and wire finishing

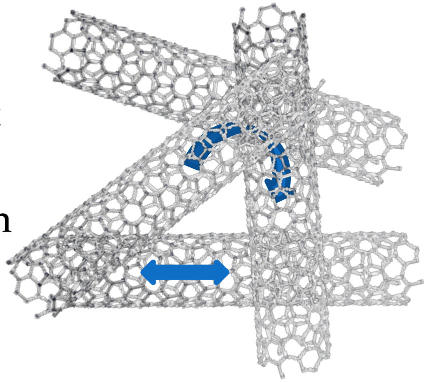
MINNESOTA WIRE Life Saving Connections

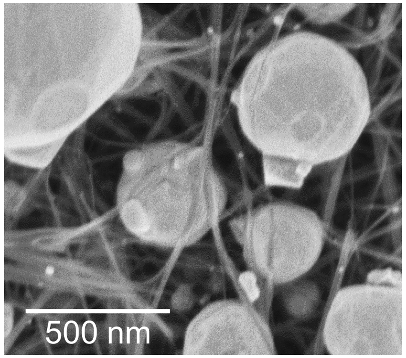
Project Objective

- What is the problem?
  - I^2R losses and excess mass leads to inefficiencies in wire electrical transport and energy conversion.
  - Potential of 1% energy savings of total US electricity consumption (source: DOE).
  - System heating to 150-250 °C exacerbates the problem due to the positive temperature coefficient of resistance (TCR) of most metals used in electrical conduction.
- What are we trying to do?
  - Bulk carbon conductors are ~10x lower conductivity than Cu/Al, but have improved TCR and density.
  - Goal: Fabricate Nanometal-Interconnected Carbon Conductors (NICCs) using carbon nanotubes (CNTs) with 28 AWG wire conductivity between 15 – 30 MS/m at 150 °C.
- Why is this difficult?
  - Individual CNT ~2 times better conductor than Cu, but bulk CNT limited by CNT:CNT junction resistance.
  - Metal integration to bridge CNTs affected by deposition technique and CNT surface "wettability".
  - Metal – CNT junctions may not be ohmic, nor coupled mechanically, and need to maintain optimal CNT transport and geometric alignment.

Temperature and Electrical Conductivity







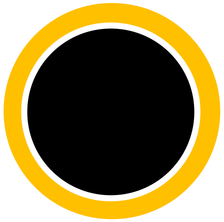
Technical Innovation

- How is it done today?
  - Physical Vapor Deposition – Provides a surface coating or shell for conductive composites.
  - Electroplating – Enables fabrication of metal-CNT composites via organic and aqueous based solvents.
  - Powder Processing – molecular-level-mixing of CNTs and metal.
- What are the limits of current practice?
  - Bilayer conductor in which metal overcoat provides majority of the electrical work; benefits are unclear.
  - At the nanoscale there exists poor connectivity between traditional conductor metals and CNTs, and delamination at elevated temperatures.
  - High mass loadings required to achieve competitive conductivities.

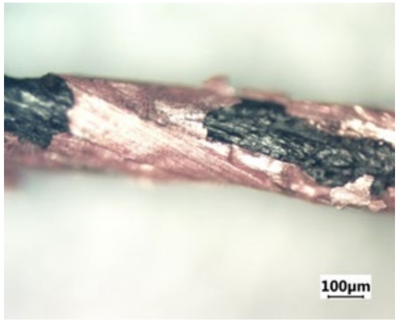
OPPORTUNITY: Leverage existing processes and develop post-production modifications to achieve:

- Effective utilization of metal will decrease conductor mass (e.g. particle size, mass, location, etc.).
- Nanoscale integration of metals via network penetration and "bridging" between CNTs.
- Improved deposition and transport through wetting metals.
- Develop relationship for CNT-metal hybrids and the TCR.

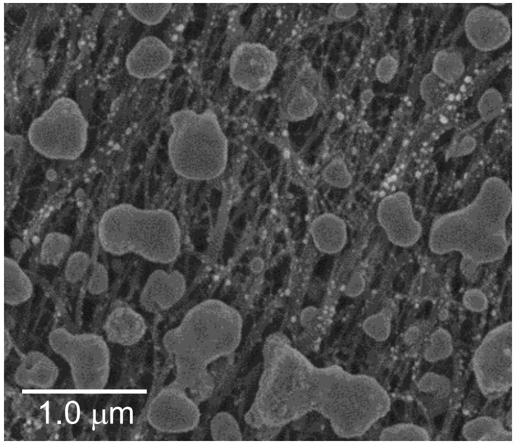
Electroplating & Physical Vapor Deposition



Discrete Layers



Network Integration and Effective Utilization of Metal

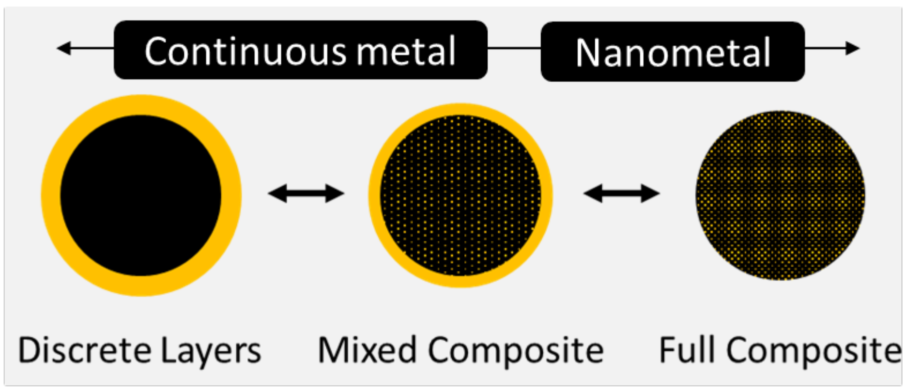


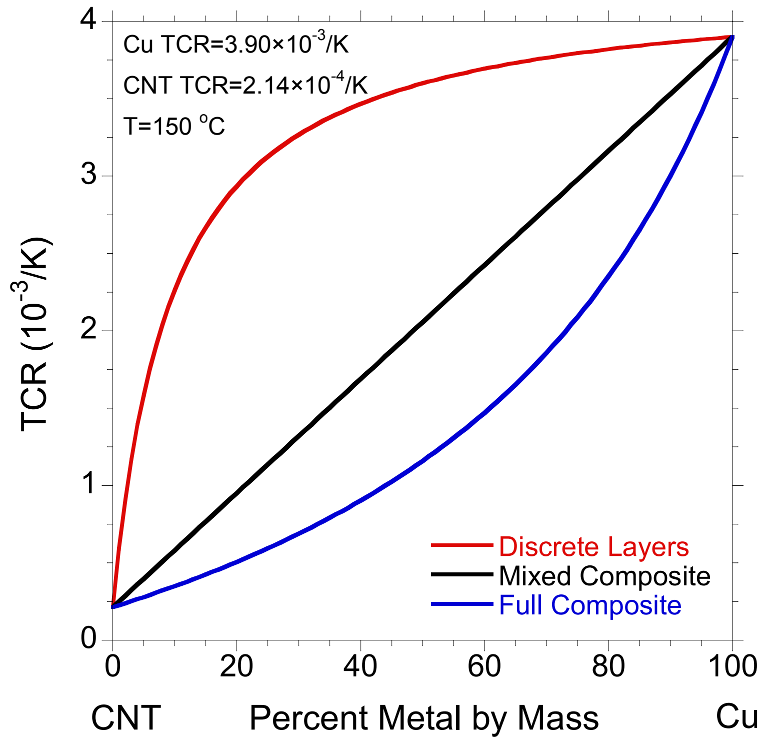
Technical Innovation

NICCs - Nanometal Interconnected Carbon Conductors

1. Efficient Utilization of Metal

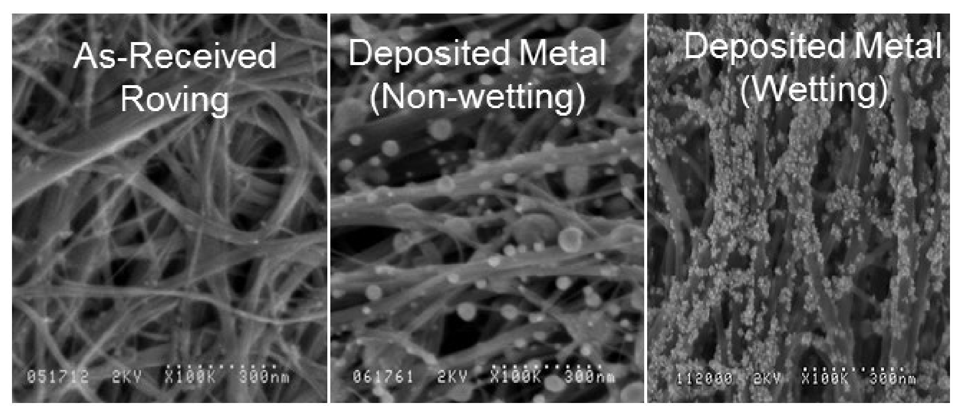
- Bridging the resistive CNT junctions with metals helps to reveal the inherent high conductivity of the CNTs while requiring low amounts of metal.
- Moving towards a fully integrated nanometal composite enables efficient metal utilization.





2. Surface Functionalization

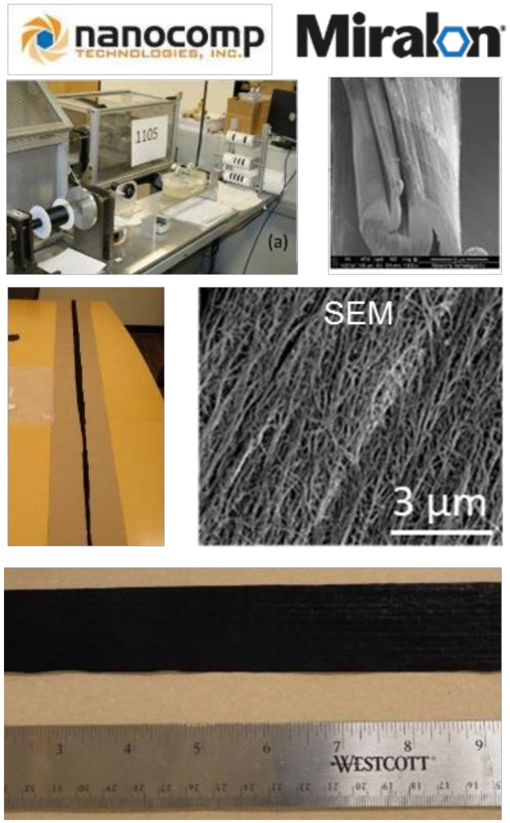
- Proper metal adhesion promotes interaction between components, enhancing their hybrid effects. CVD can provide nanometal seeds for electrodeposition and interconnects.
- Provides electrical contact while suppressing delamination at elevated temperatures.



Technical Approach

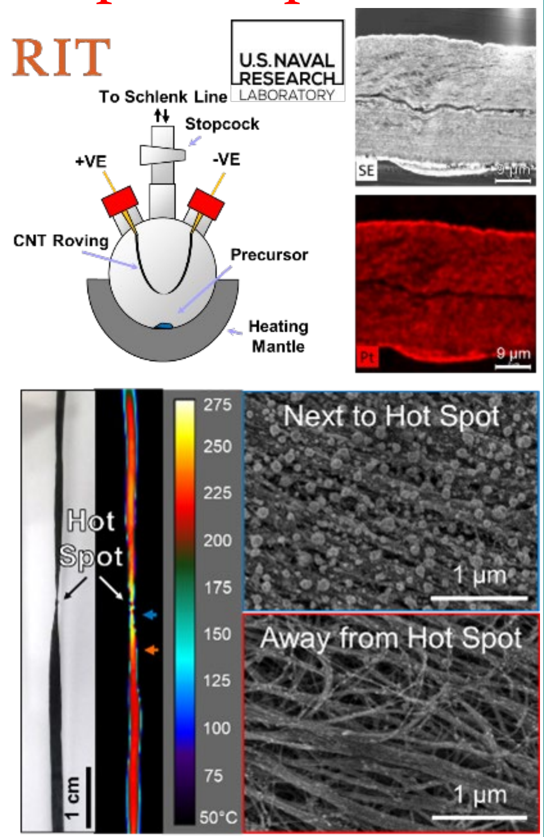
Technical approach for the project: Combine RIT and NRL knowledge of CNT wire modification with Nanocomp Technologies and MN Wire and Cable knowledge of scalable wire production and finishing.

CNT Production



Using commercially scaled CVD process to enhance production roving prior to spinning

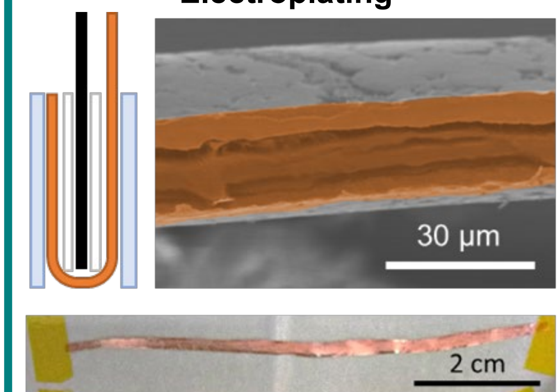
Vapor Deposition



Site-selective deposition at junction sites and hot spots through Joule heating

Finishing

Electroplating



Inexpensively interconnect metal seeds

MINNESOTA WIRE

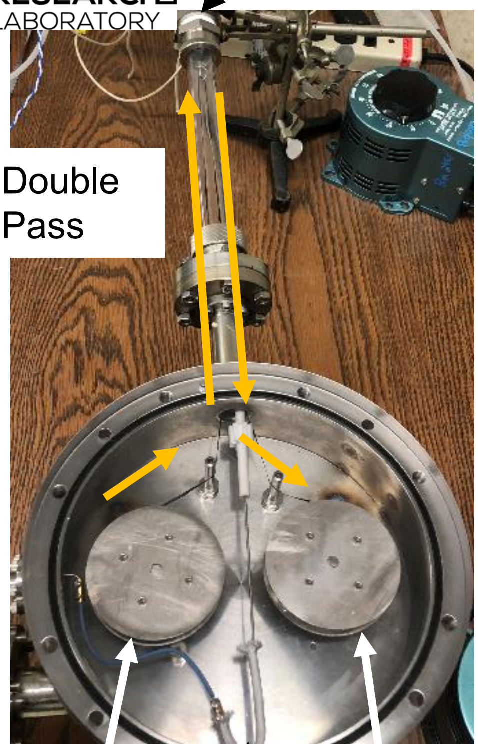
Braiding, Coating and Termination

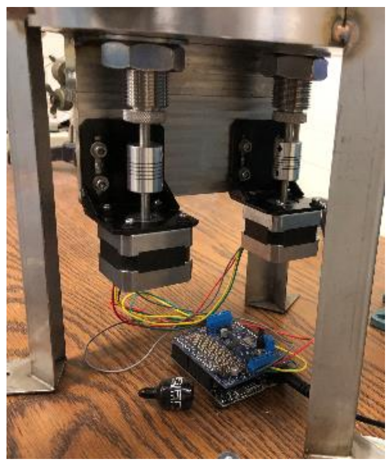
Passivation and preparation for use

CNT Materials → NICCs → Advanced Wires

Technical Approach

NRL facilities produce coated CNT materials using a pilot scale vapor-phase deposition technique which can support spooling.





- CNT roving is Joule heated
- Variable speed and path length
- Double-pass through deposition zone

Industrial scale manufacturing of bulk CNT materials achieved through CVD synthesis from 10 to 35 tex.

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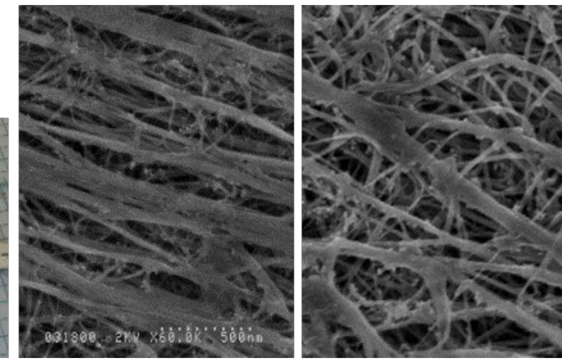
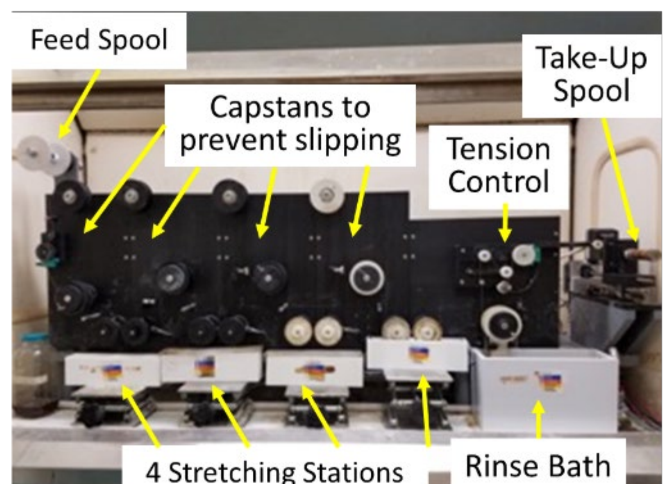


Electrochemical stretching and post-processing to promote CNT alignment and doping.



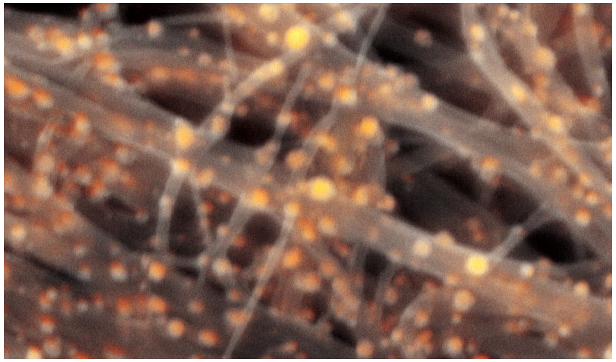
Results and Accomplishments

Accomplishments since 2018:

- CVD for site-selective deposition using novel filament heating with metal adhesion particles (Provisional Patent No. 62/698321).
- Large-scale vapor-phase deposition capabilities developed at NRL with 20% mass loading of nanometal seeds over a 2 m conductor.
- Achieved 28 MS/m at R.T. in a Cu-CNT hybrid conductor (Leggiero, et al. *ACS Appl. Nano Mat.* **2019** 2 (1), 118-126).
- High tex roving materials (i.e. 35 tex ~28 AWG diameter) with comparable performance manufactured at NCTI.
- Conductivity of 12.8 MS/m achieved at 150 °C on a finished 10 cm ribbon conductor via CVD deposition and electroplating.

Work to be completed:

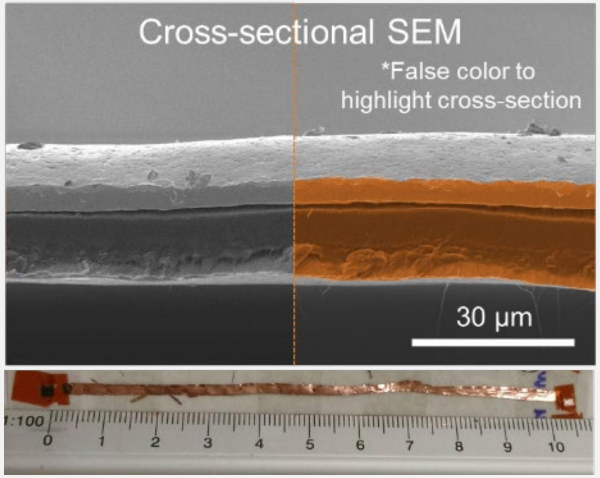
- Modify mass loading of wetting metals for efficient utilization with CVD and electroplating.
- Optimize production of 40 tex roving material.
- Develop strategies for braiding and finishing of conductors.
- Utilize S^2VPNS and electroplating to produce 28 AWG conductor with ~1 m length and conductivity of 15-30 MS/m at 150 °C.



Cu particles in image are false colored

NRL S^2VPNS System

Cu/CNT Ribbon Conductor



Transition (beyond DOE assistance)

- What is the commercialization approach?
  - Leveraging highest production continuous CNT CVD growth and spooling capabilities in the US. – Plans to produce 40 metric tons yearly.
  - During year 3, RIT and NRL will collaborate with NCTI to propose a working process that can be implemented at scale.
  - During year 3, Minnesota Wire will provide expertise and demonstration of CNT wire braiding, coating, and termination.
- What is the transition to the commercial marketplace?
  - Seek early adoption by DoD (Navy/Air Force) & Aerospace industry.
    - Energy savings through improved conductivity: Motors, generators, electricity distribution.
    - Weight reduction for aerospace and vehicle applications – additional fuel savings.
    - Simplification of heat-dissipation systems (e.g. data centers).
  - Electric vehicle/rotating machinery gradual adoption as costs reduces and technologies mature:
    - Uniformity of wires meet specifications.
    - Production yield meets demand.

MINNESOTA WIRE
Life Saving Connections

Outcome: Scalable nanometal CVD approach can be integrated with CNT post processing to directly impact manufacturing.